Systems and Internet Infrastructure Security

Network and Security Research Center
Department of Computer Science and Engineering
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Securing End-to-End Provenance: A Systems and Storage Perspective

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Provenance

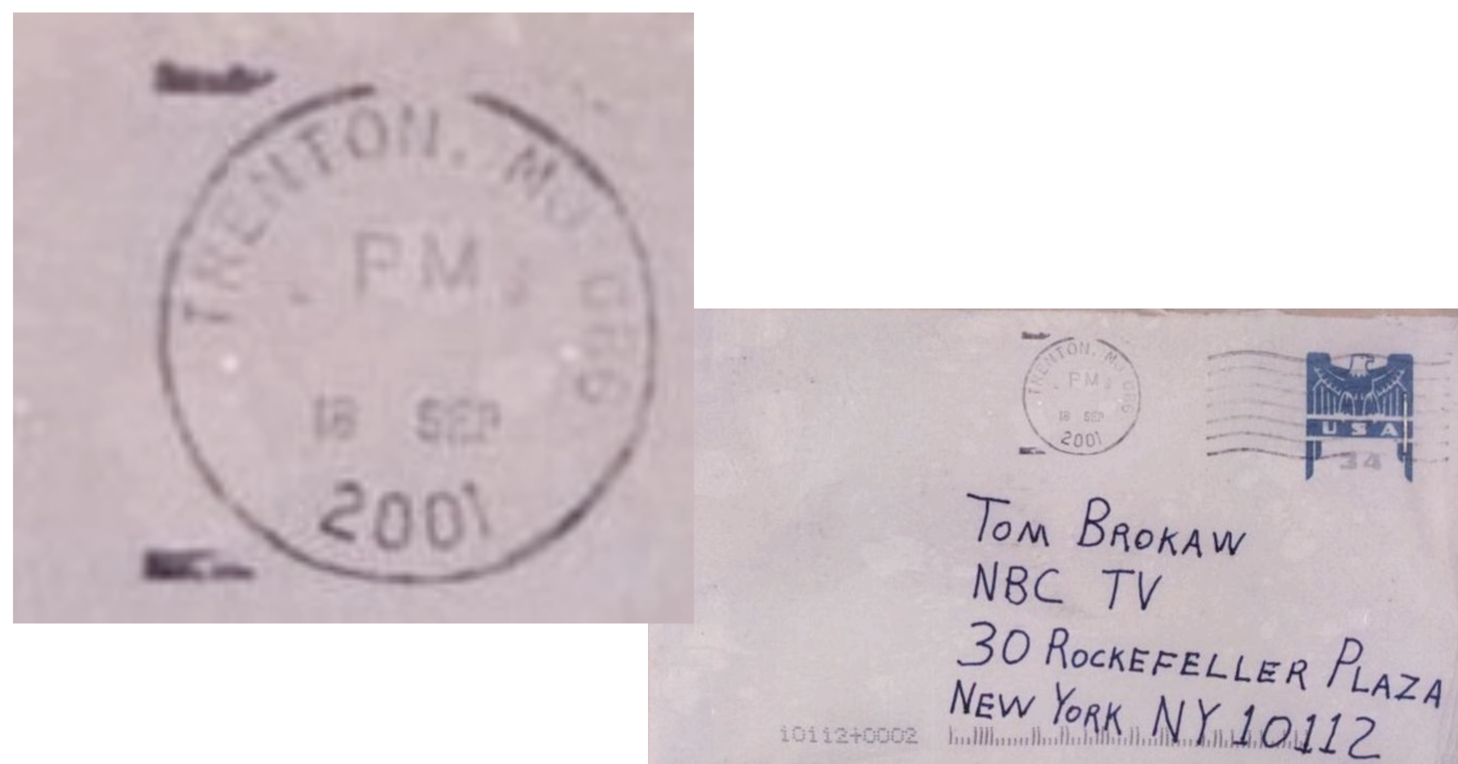
- Shuttle launch relies on thousands of systems and millions of parts all working together correctly: enormously complex
- File systems for HEC are similarly complex - originates from *many sources* and synthesized by *complex and sometimes hidden* processes
- What does the data mean and how can we interpret and analyze it?

Data Provenance

- Data provenance allows us to answer the following questions about the origin of data:
  - *Who or what* contributed to the generation of this data?
  - *What* is the data based upon?
  - *When* was the data generated?
  - *Why* was it generated?
  - *How* was it generated?
- A history of the object from origin through subsequent modifications is evidenced by a *provenance chain* (DAG)

End to End Provenance System

- Why another provenance collection system?
  - Strong security guarantees
  - Distributed provenance collection
  - EEPS will achieve the above two goals efficiently in high end computing systems



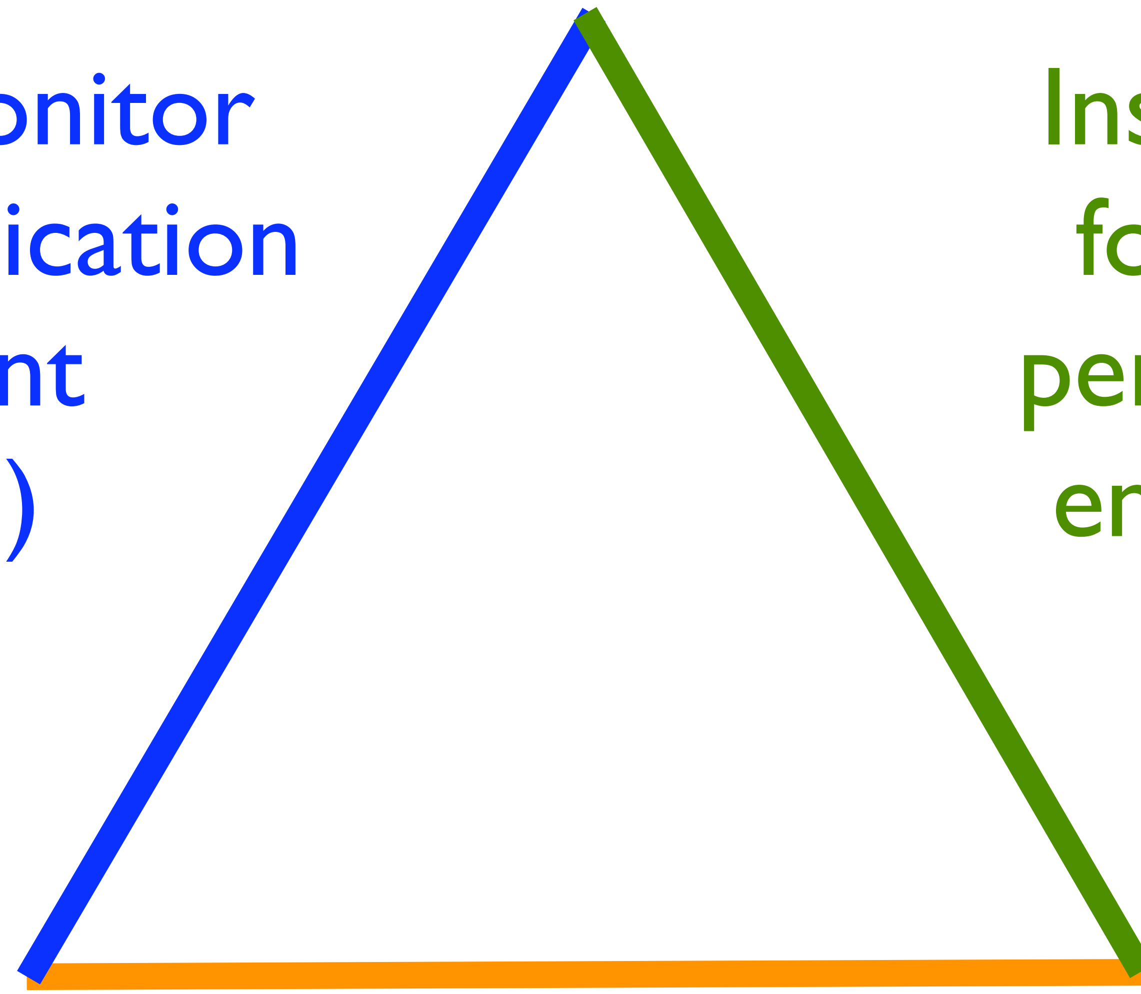
Secure Provenance Collection

- Provenance monitor (PM) analogous to reference monitor concept
- Three guarantees
  - Complete mediation
  - Tamperproofness
  - Verifiability
- Beyond authentication of records
  - Integrity/Trustworthiness of recording instrument and provenance-enhanced applications

Project Initiatives

Provenance monitor system and application development (McDaniel)

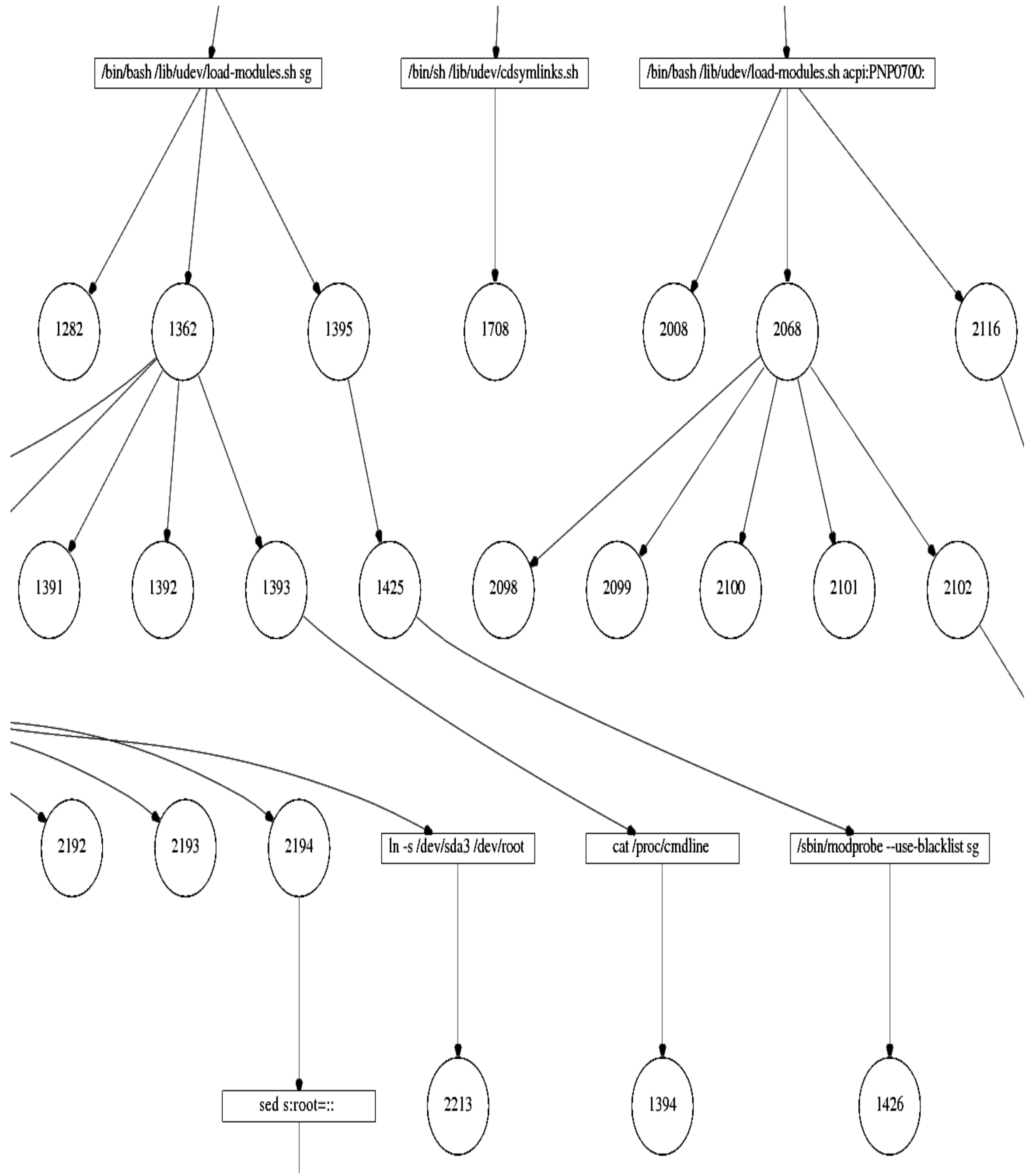
Instrumentation for measuring performance and energy (Zadok)



Provenance chain constructions and query management (Sion, Winslett)

Provenance Monitor

- Implementing LSM-based provenance monitor
  - LSM for complete mediation, tamperproofing
- Tracking provenance of entire VM runs
  - Created graph of entire process ancestry
  - Investigated visualizations which included file reads/writes
- Exploring potential for secure multi-host and interdomain provenance



Autonomously Secure Disks

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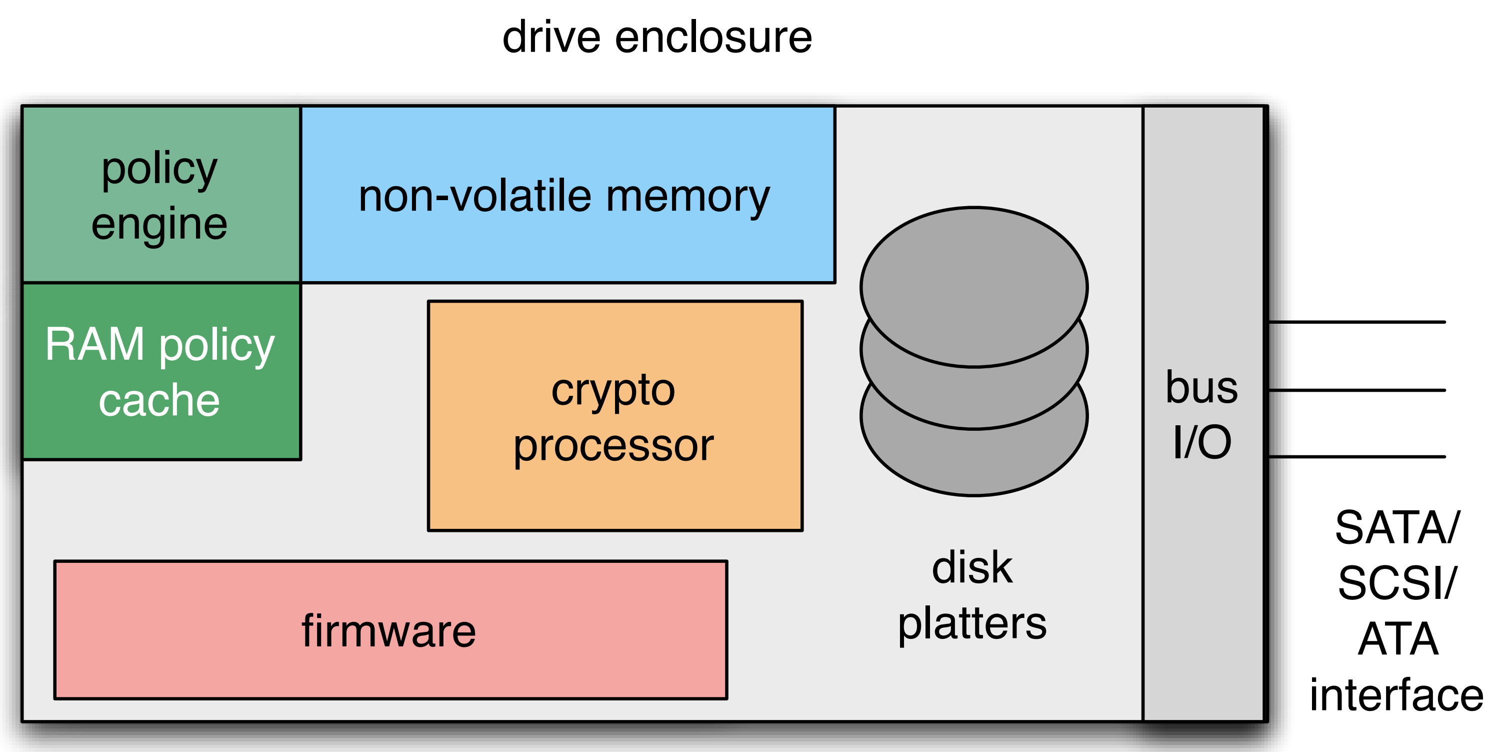
- Enforce security perimeter at external I/O interface
  - How? Store all security metadata *including provenance information* within the drive itself



"New Security Architectures Based on Emerging Disk Functionality", IEEE Security and Privacy, Sept/Oct 2010

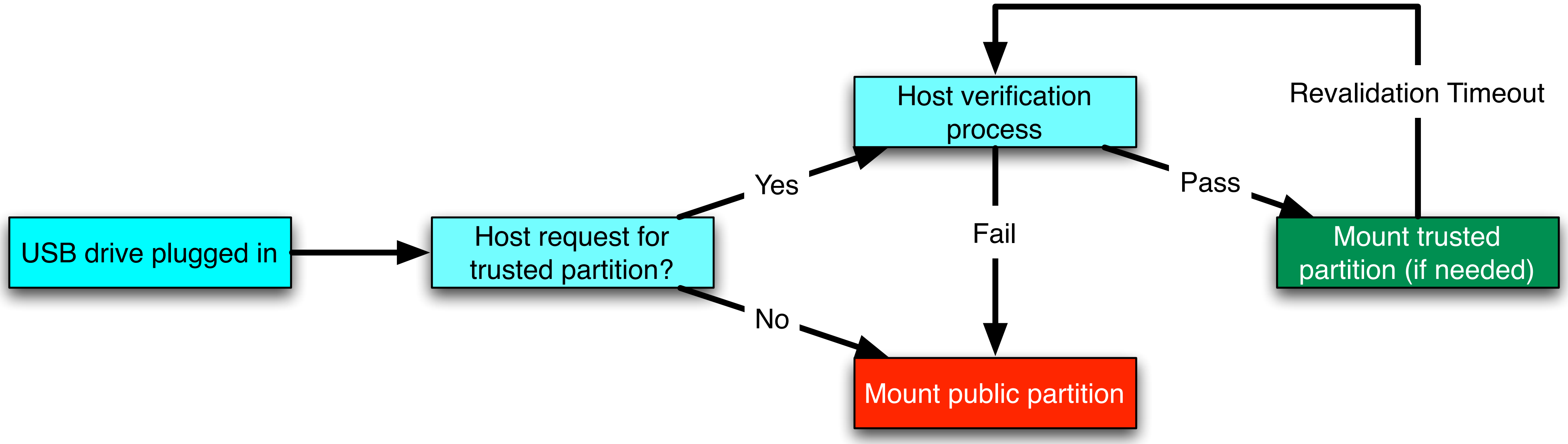
Host Validation

- Portable storage holds more and is more ubiquitous than every before (256 GB flash drives)
  - Public/private data on devices, want to share some info but protect other data

- How can we solve these issues?
  - Only allow registered devices on system
  - Virus scanning on flash drive
  - *General problem*: How do we know if the system we share data with is in a good (valid) state? Can we collect a provenance record relating to this data?

Kells

- USB storage device performs *attestations* with host in order to determine its integrity state
- Periodically repeat attestation to get continuous guarantee of host integrity
- Allow access to *trusted* partition only if system is in a good state



Continuous Attestation

- Support framework for runtime monitoring on system
  - Patagonix, Pioneer, BIND, LKIM, etc.
- Continuous attestation gives assurance that the system is in a good state
  - Length of time between attestations can be parameterized by an attestation period Δ_t
  - Acts as *security heartbeat*
- *Quarantine buffer* on storage device holds writes until system state is attested

Kells Security Properties

- **SEC:** *"Any read request completed by Kells was made while the host was in a good state."*
  - attestation received within Δ_t of the request and the system was not rebooted
- **INT:** *"Any write request completed by Kells was made while the host was in a good state."*
  - same dependency on attestation received within Δ_t as with **SEC**

$$
\begin{aligned}
(\mathbf{SEC}) \vdash \;\; \forall \;\; & (\mathtt{t}_{\mathtt{req}}, (l, n)), (\mathtt{t}_{\mathtt{att}}, sig), t \;\text{ s.t.} \\
& (\mathtt{t}_{\mathtt{req}}, (l, n)) = \mathsf{Recv}(\mathcal{D}) \;@\; t \\
\wedge \;\; & (\mathtt{t}_{\mathtt{att}}, sig) = \mathsf{Recv}(\mathcal{D}) \\
\wedge \;\; & e = \mathsf{SRead}(\mathcal{D}, (t, \mathtt{t}_{\mathtt{req}}, (l, n)), (\mathtt{t}_{\mathtt{att}}, sig)) \\
\supset \;\; & \mathsf{GoodState}(\mathcal{H}, (t, \mathtt{t}_{\mathtt{req}}, (l, n)), (\mathtt{t}_{\mathtt{att}}, sig))
\end{aligned}
$$

$$
\begin{aligned}
(\mathbf{INT}) \vdash \;\; \forall \;\; & (t, \mathtt{t}_{\mathtt{req}}, (l, n)), (\mathtt{t}_{\mathtt{att}}, sig) \;\text{ s.t.} \\
& (t, \mathtt{t}_{\mathtt{req}}, (l, n)) = \mathsf{Peek}(\mathcal{D}) \\
\wedge \;\; & (\mathtt{t}_{\mathtt{att}}, sig) = \mathsf{Recv}(\mathcal{D}) \\
\wedge \;\; & \mathsf{SWrite}(\mathcal{D}, (t, \mathtt{t}_{\mathtt{req}}, (l, n)), (\mathtt{t}_{\mathtt{att}}, sig)) \\
\supset \;\; & \mathsf{GoodState}(\mathcal{H}, (t, \mathtt{t}_{\mathtt{req}}, (l, n)), (\mathtt{t}_{\mathtt{att}}, sig))
\end{aligned}
$$

Bottom Line: Provides formal proof that data is protected.

Future Project Goals

- Revealing file access patterns
  - What is "least privilege?"
  - Forensic details of file and block access: "Which host accessed this particular data and where may that information have been disseminated?"
- Information flow systems
  - Provenance as enriched information flows
- Provenance calculus
  - Formalism for expressing and querying provenance data
  - Working toward more rigorous definitions of provenance
  - Potential for machine learning applications

Performance Enhancements

- Provenance monitor profiling
  - Enhanced profiling tools
  - Profiling provenance collection for workloads from scientific domains
  - EEPS calibration for a particular environment
  - LSM instrumentation
- Cost models for provenance collection
  - Hardware and storage requirements ($/GB)
  - New cost models based on types of provenance data collected and system architectures

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Securing End-to-End Provenance

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Systems Problems

- Reliable high-volume data transmission from kernel to userspace
  - Currently using Linux relay mechanism
  - Investigating other means to increase reliability
- Inclusion of filenames in inode tracking
  - LSM provides little context here
  - Would provide additional information during analysis

Distributed PM

- Challenges in distributed provenance
- Domain specific policies for:
  - Auditors - confidentiality considerations
    - Cryptographic commitments [Hasan'09]
  - Divergent modification histories
    - Plausible version history
    - If necessary, plausible history may be checked against previous subjects in the ownership chain

Distributed Environments

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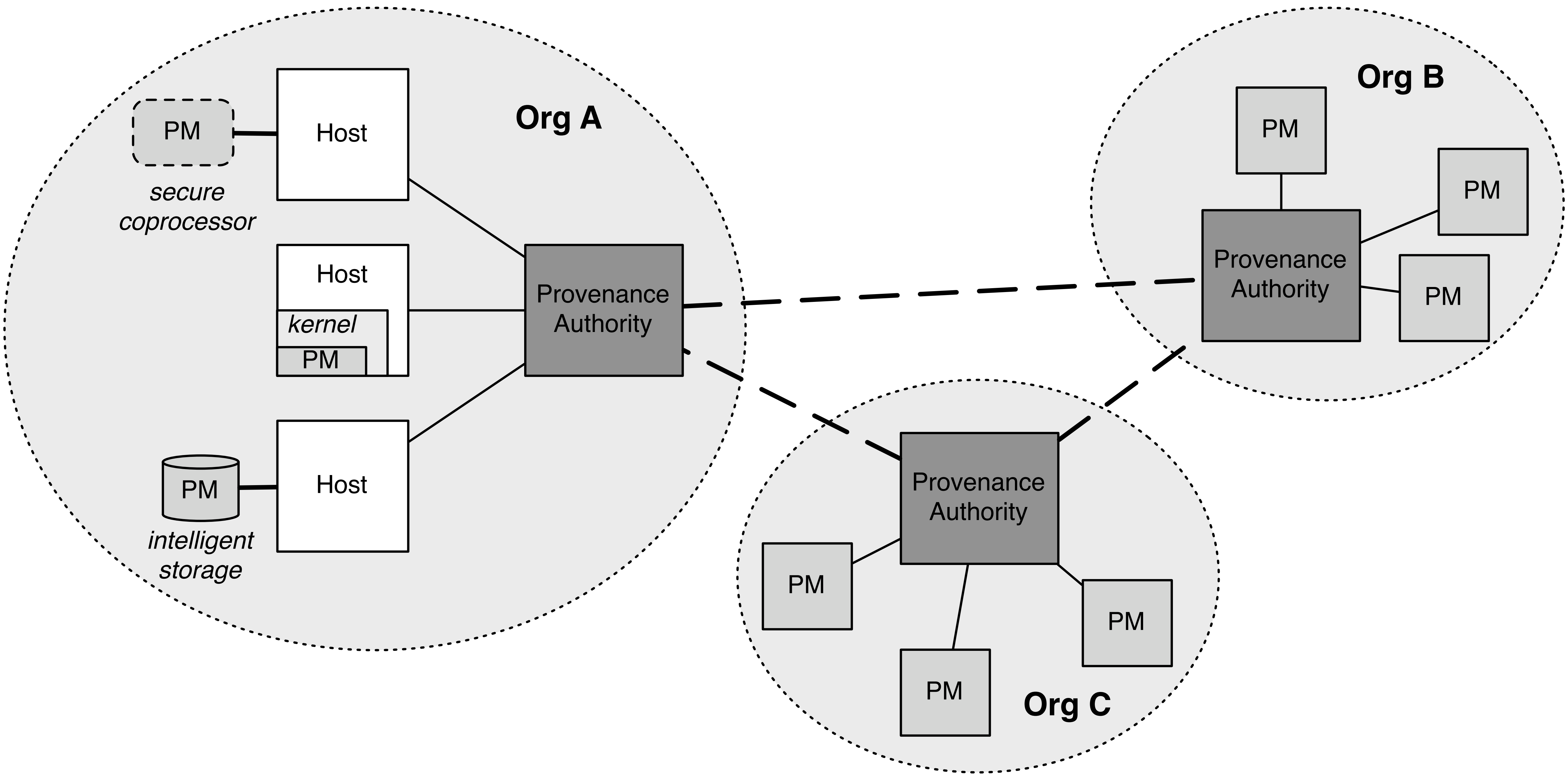
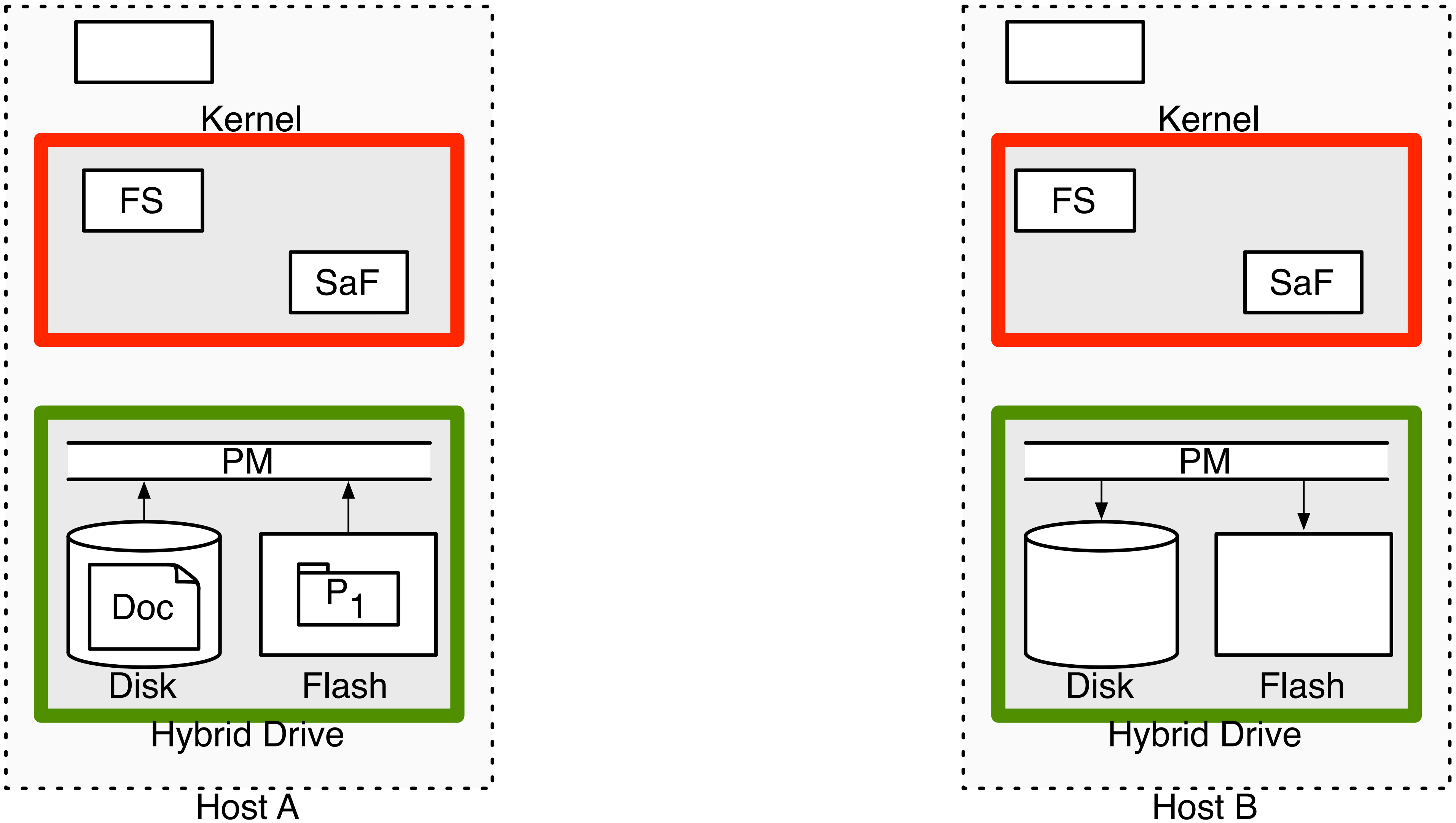
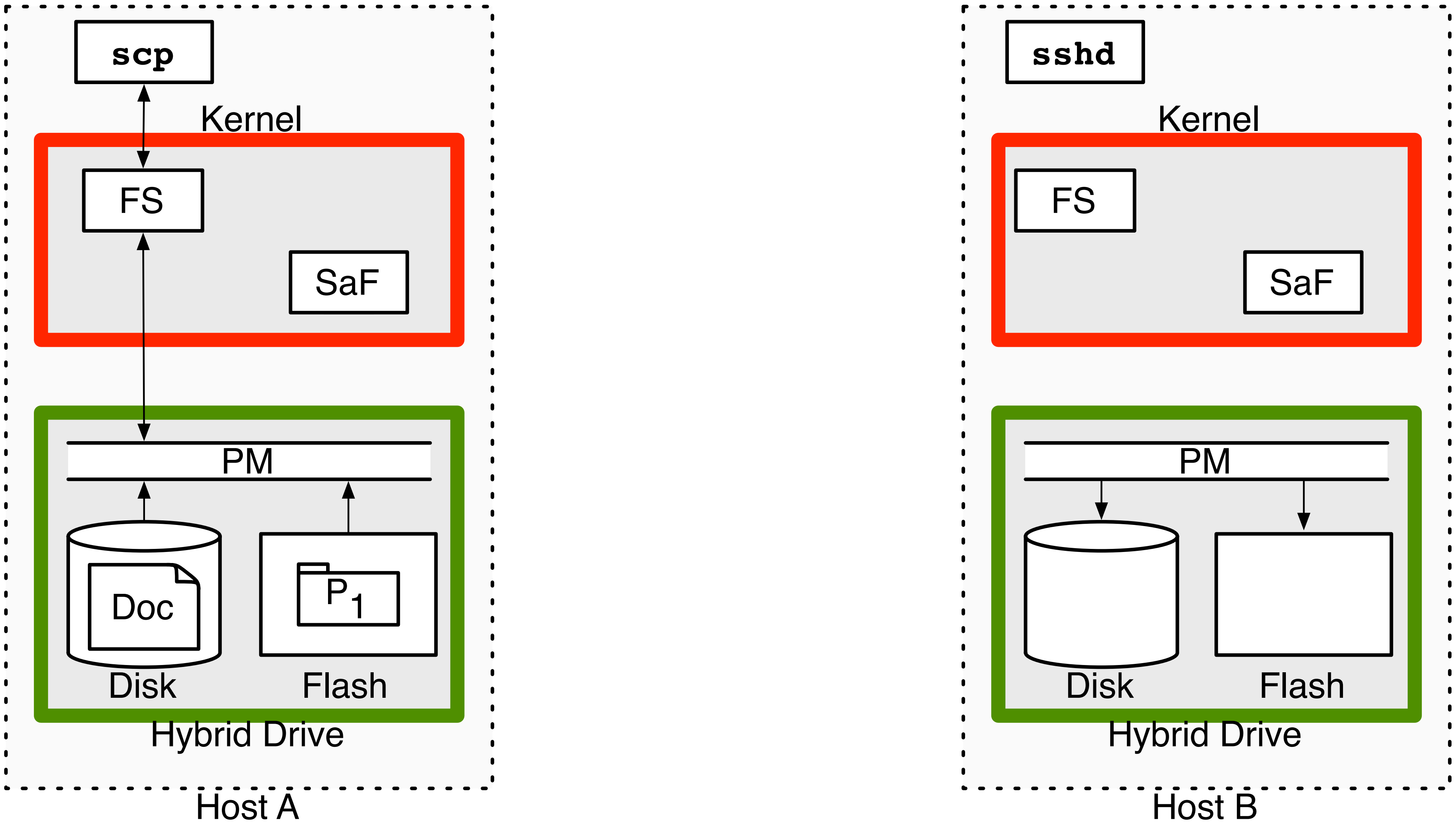


Distributed Example



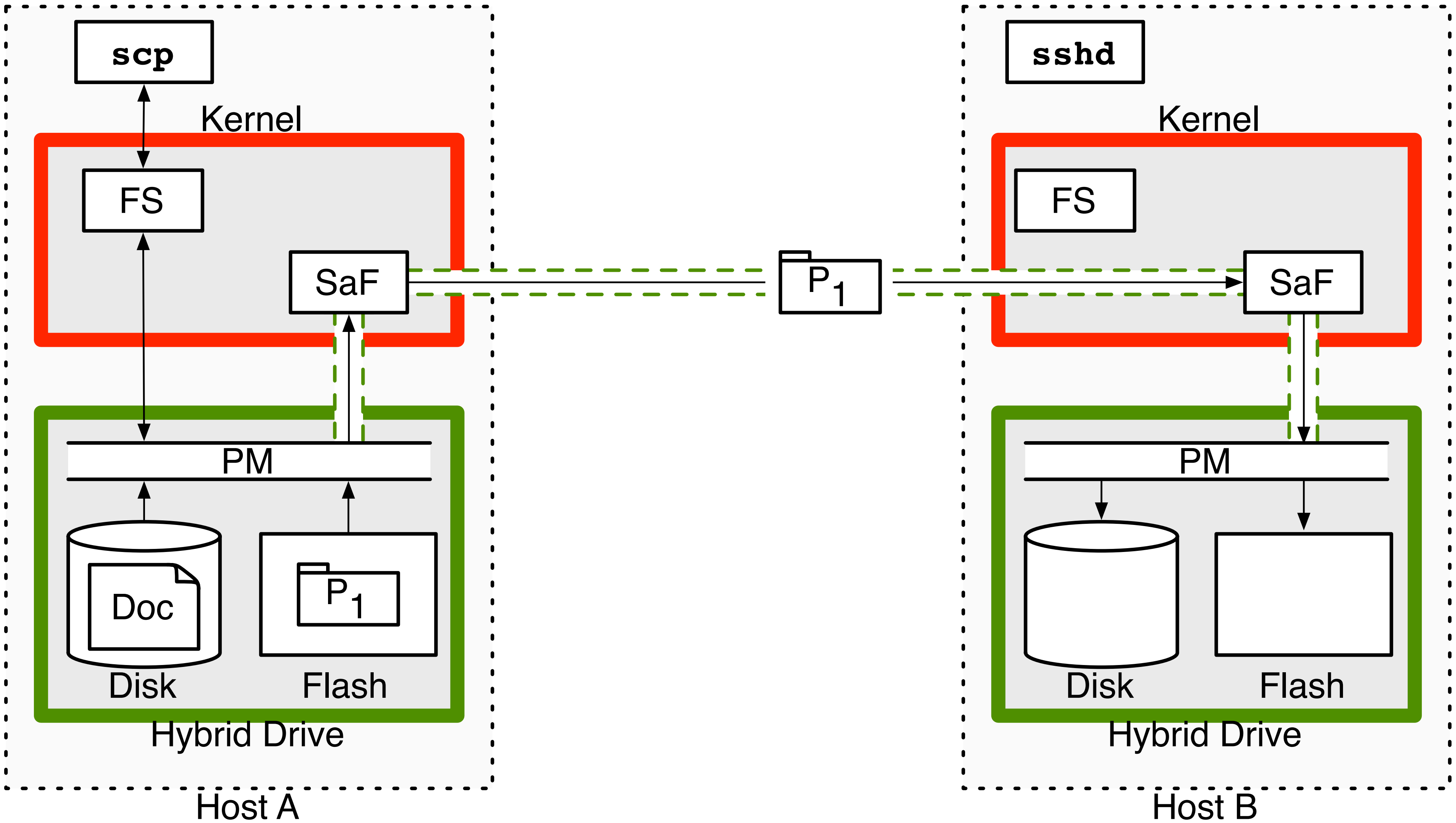
Example: File transfer between hosts with untrusted OSes and trusted storage

Distributed Example



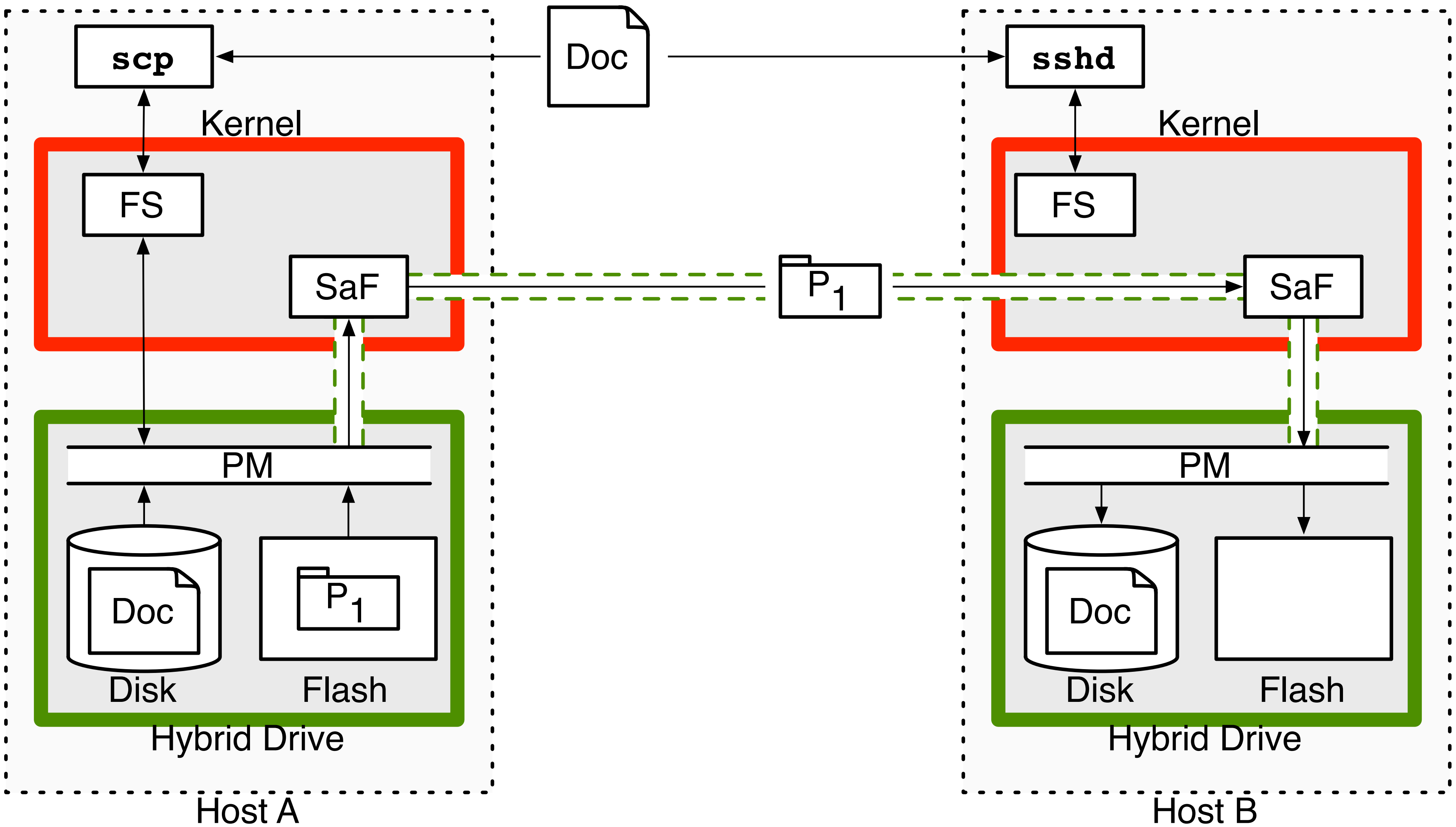
A program initiates a request for the file.

Distributed Example



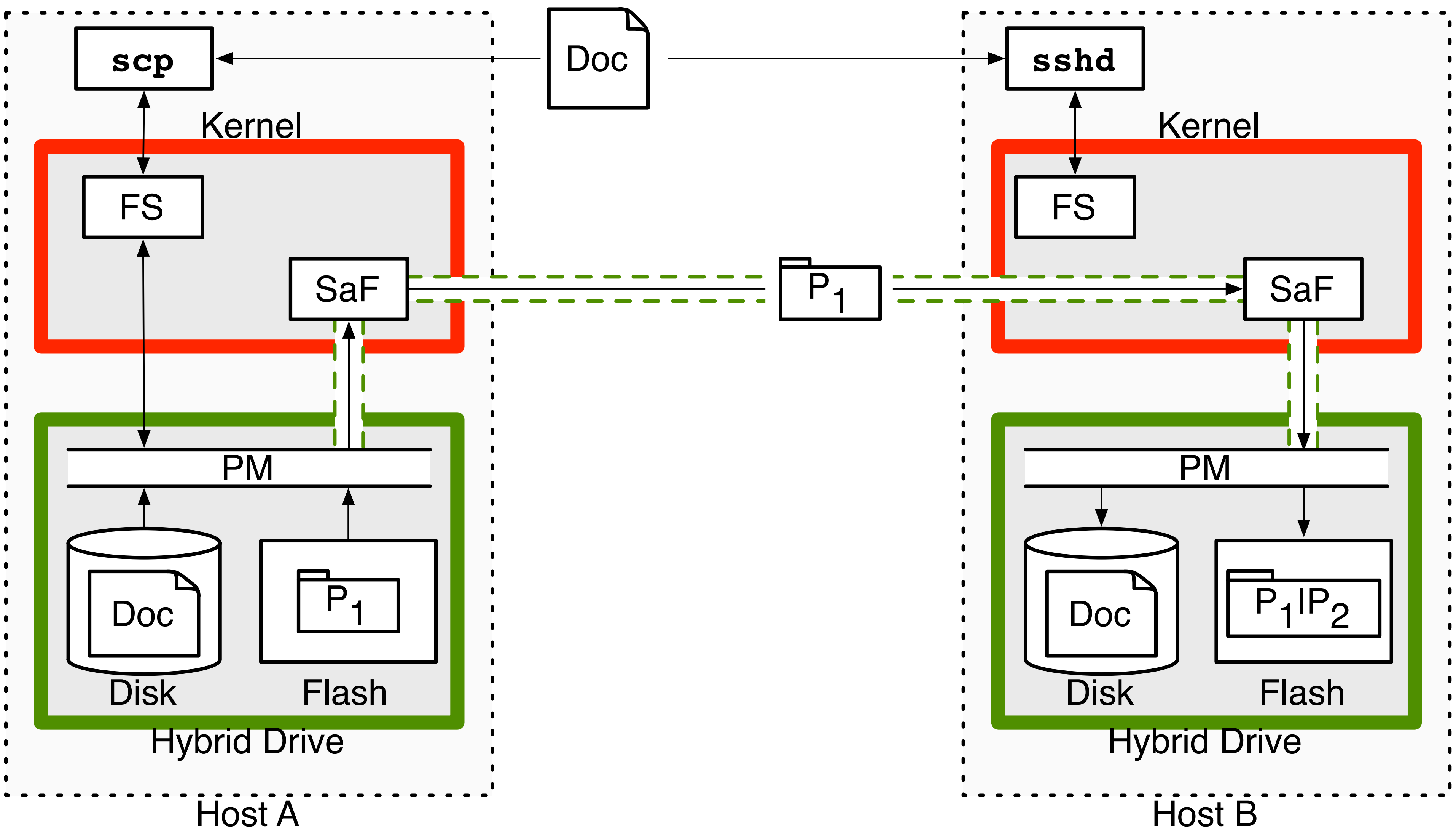
A secure tunnel is established between disks through the untrusted OS.

Distributed Example



The document is transferred as normal.

Distributed Example



The destination disk checks the integrity once the write-through is completed and appends a new provenance entry.

Distributed Provenance Overheads

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- Overhead increases monotonically as data is shared.
- Two implications:
  - Storage costs within a single domain
    - High sharing factor: redundant provenance data
    - Long per-host modification histories: higher redundancy factor
    - Even though document size may remain constant!
  - Audit costs between domains
    - As sharing of a document increases, the computational cost of sharing increases